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Erosion, transport and deposition of sediments by the tropical rivers of India

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Abstract Some major tropical rivers of India — the Cauvery, Krishna and Godavari — were sampled to characterize their sediment transport. On the basis of our observations their sediment loads have been computed and compared with those of the major rivers of the world. Monthly and annual variations in sediment transport as a function of time and space have been observed. The mean annual sediment transport of the Godavari, Krishna and Cauvery have been estimated to be 170, 4 and 1.5 t x 10^6 respectively. The bulk of the sediment transport (>95%) takes place within a three month segment of the monsoon period. The size distribution data for suspended sediment in the Godavari River indicate that the relative contribution of the different grain sizes to annual sediment load ranges from 23 to 2% for coarse, from 30 to 5% for medium and from 87 to 49% for fine sediment. Mineralogically, the suspended sediment of these rivers is characterized by an abundance of montmorillonite with minor amounts of illite, kaolinite and chlorite. Rates of sedimentation in sediment cores collected from the deltaic region of the river basins were determined by the excess ^{210}Pb technique. Sediment deposition rates of 1.1 cm year^{-1} for the Krishna River and 0.35 cm year^{-1} for the Cauvery River were obtained.

Erosion, transport et dépôt de sédiments dans les fleuves tropicaux de l'Inde

Résumé Quelques grands fleuves tropicaux de l'Inde, le Cauvery, la Krishna et le Godavari ont fait l'objet de prélèvements pour caractériser les quantitées de sédiments transportés. Sur la base de nos observations leurs charges en sédiments ont été calculées et comparées avec celles des grands fleuves du monde. On a observé les variations annuelles et mensuelles de transport de sédiments en fonction du temps et de l'espace. Les transports de sédiments moyen annuel du Godavari, de la Krishna et du Cauvery ont été estimés respectivement à 170, 4 et 1.5 t × 10^6. L'essentiel du transport de sédiment a lieu pendant une période de trois mois au cours de la mousson. Les données concernant la distribution granulométrique des sédiments en suspension pour le Godavari indiquent que la contribution des différentes catégories granulométriques à la charge annuelle de sédiments varie de 23 à 2% pour les éléments grossiers, de 30 à 5% pour la taille intermédiaire et de 87 à 49% pour les éléments fins. Au point de vue minéralogique, les sédiments en suspension dans ces fleuves sont caractérisés par l'abondance de montmorillonite avec de faibles proportions d'illite, de kaolinite et de chlorite. Le taux de sédimentation dans les carottes de sédiments prélevés dans les régions deltaïques des ces fleuves a été déterminé par la technique de l'excédent de ^{210}Pb. Le taux de dépôt de sédiment a été trouvé égal à 1.1 cm an^{-1} pour la Krishna et de 0.35 cm an^{-1} pour le Cauvery.

INTRODUCTION

Rivers are important geological agents for erosion, transportation and deposition. Over the past two or three decades growing awareness of the wide ranging environmental significance of suspended sediment transport by rivers has generated a considerable body of information concerning the magnitude of sediment yields and their control by human activity, climate and other catchment characteristics. Quantitative estimates of river transport have, for example, been assembled on a global scale by Holeman (1968) and Milliman & Meade (1983); on a regional scale by Grove (1972), Lisitzin (1972), Subramanian (1979), Hu Ming Hui *et al.* (1982) and Meade (1983); and for individual river basins of India by Raymahasay (1970), Abbas & Subramanian (1984), Ramesh & Subramanian (1986) and Biksham & Subramanaian (1988). More than 70% of the present day estimated global sediment flux of 13.3×10^9 t is contributed by medium-size and small-size river basins (Milliman & Meade, 1983). Studies of these basins not only improve the data base of the global estimates, but are also useful in increasing our understanding of continental fluvial processes.

The present study of the major tropical rivers of India, including the Godavari, Krishna and Cauvery is an attempt to understand the sediment fluxes and controlling factors involved. The tropical rivers constitute only a small part of the Indian river system, but they are nevertheless important due to the area that they drain and the density of population that they serve.

AREA OF STUDY

The Godavari, Krishna and Cauvery River basins together account for over 60% of the tropical Indian drainage system. They rise in the Western Ghats (the mountain range along the Arabian sea) and flow about 1000 km before discharging into the Bay of Bengal. The river basins experience a semiarid climate and are fed by the monsoonal rainfall. A map of their basins and the underlying geological formations is provided in Fig. 1.

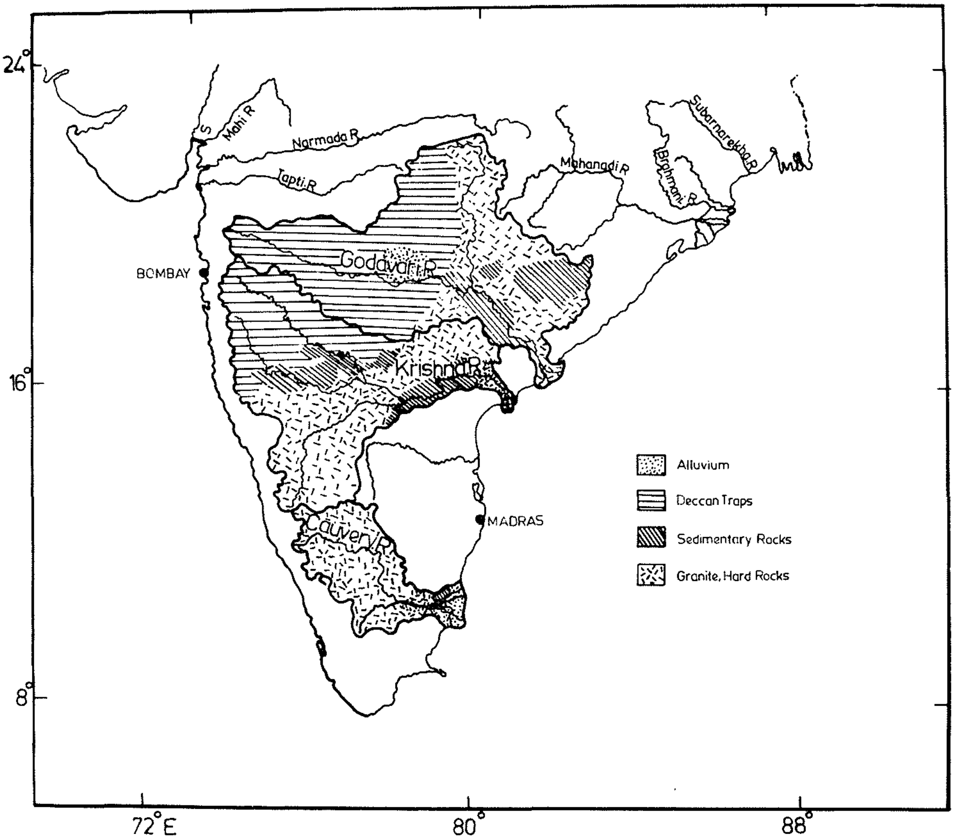

Fig. 1 Map of the Godavari, Krishna and Cauvery River basins showing the major rock formations.

METHODOLOGY

One-litre water samples were collected in mid-river from the locations shown in Fig. 2 on a number of occasions since 1975, to broadly cover the seasonal and annual variations. The locations were chosen so as to represent all regions of the river basin, the major tributaries, their zones of mixing with

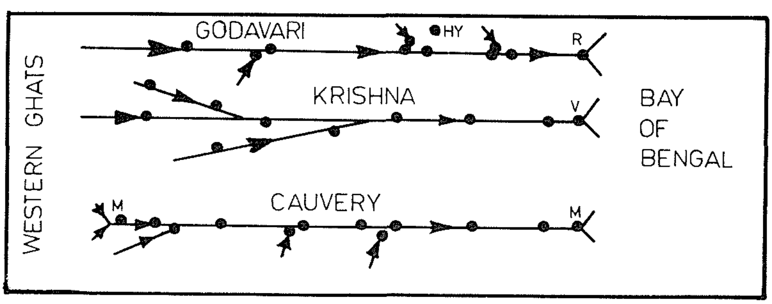

Fig. 2 Sampling locations.

the river and the major urban areas, dams etc. The water samples were filtered through 0.45 μm millipore filters and the total suspended matter concentration was estimated. The size distribution of the suspended sediment was determined using a model TA 11 Coulter Counter interfaced with an Hewlett-Packard desk-top computer. Minerological studies were undertaken with a Philips X-ray diffractometer using Cu K α radiation and a Ni filter. Additional data on discharge and sediment load were obtained from several published/unpublished reports of government agencies in India.

RESULTS AND DISCUSSIONS

The average annual runoff and sediment load of the Godavari, Krishna and Cauvery are listed along with some hydrological data in Table 1. The values

Table 1 Mean discharge and sediment transport of tropical Indian rivers and major world rivers

River	Station	Drainage area (km^2)	Annual runoff ($10^6 m^3$)	Sediment transport (10^3 t $year^{-1}$) Total	Monsoon
Tropical Indian rivers					
Godavari	Rajhamundry	313 147	92 245	170 000	163 000
Krishna	Vijayawada	251 360	32 397	4 110	4 100
Cauvery	Musiri	66 243	11 510	1 500	1 320
Mahanadi	Tikarapara	88 320	54 510	30 700	-
Narmada	Garudeshwar	87 892	46 673	69 700	-
Tapti	Savkheoa	49 136	9 713	24 700	-
Pennar	Somasila	48 660	5 203	6 900	-
Brahmani	Samal	28 200	16 340	20 400	-
Mahi	Kadana	25 501	10 817	9 700	-
Major world rivers					
Ganges		750 000	493 000	329 000	
Brahmaputra		580 000	510 000	597 000	
Huangyeo		745 000	48 000	1080 000	
Amazon		6300 000	5500 000	900 000	
Yangtze		1950 000	1063 000	487 000	
Irrawady		430 000	422 000	285 000	
Magdalena		240 000	236 000	220 000	
Mississippi		3267 000	580 000	210 000	
Orinoco		950 000	946 000	210 000	
Mekong		795 000	666 000	160 000	

Sources: Tropical Indian Rivers (Subramanian, 1987); Ganges (Abbas & Subramanian, 1984); Brahmaputra (Subramanian, 1979); major world rivers (Milliman & Meade, 1983).

for other tropical rivers in India and for some major rivers of the world are also given for comparison. The Godavari River alone transports more than 50% of the total sediment load of all the tropical Indian rivers. It is the largest sediment source to the Bay of Bengal from India, after the Ganges, and accounts for 15% of India's annual sediment budget. On a global scale the Godavari ranks as the ninth largest sediment transporting river (Biksham & Subramanian, 1988), which clearly indicates that in global terms certain medium or minor basins may be very significant, although their basin area and discharge may be relatively small. Unlike the Godavari, the Krishna and Cauvery are mechanically less active and contribute relatively less sediment compared to other Indian and world rivers. The sediment loads carried by Ganges and Brahamaputra are very high because they drain the highly erodible Himalayan mountains.

FACTORS CONTROLLING EROSION AND SEDIMENT TRANSPORT

Basin geology

The rock formations in the drainage basin are one of the key factors in controlling the sediment transport by a river. To demonstrate the extent of this geological influence on sediment transport by the tropical Indian rivers, the rock types in the basins can be categorized into three groups, namely, granite and hard rocks (generally pre-Cambrian or older), Deccan traps (Tertiary), and sedimentary rocks (pre-Cambrian or younger), based on their erodibility (Fig. 1). The distribution of rock types in the Godavari basin and their relative contribution to the annual sediment load are summarized in Table 2. Sedimentary rocks in the Godavari basin contribute a relatively large sediment load, as might be expected, because of their high degree of erodibility. The Deccan traps occupy nearly half of the basin area and contribute almost the same proportion of sediment. The contribution from granites and hard rocks to the annual sediment load is compared to their areal distribution. These rocks are relatively stable and weathering is limited (Garrels & Mackenzie, 1971). Over 80% of the drainage areas of the Krishna and Cauvery Rivers are made up of granites and hard rocks and the sediment yields from these drainage basins are in consequence very low.

Erosion rates in the tropical Indian region are shown in Fig. 3. It is obvious from this figure that there are two major erosion zones. Erosion rates are higher in the central Indian region whereas they are lower in the

Table 2 *Contribution to the total suspended sediment load by individual rock types in the Godavari basin*

Rock type	*% of basin area*	*Annual sediment load (T_S) ($T \times 10^6$)*	*% of T_s*
Granite and hard rocks	*39*	*27*	*16*
Deccan traps	*48*	*87*	*51*
Sedimentary rocks	*13*	*13*	*33*
TOTAL	*100*	*170*	*100*

Source: *Biksham & Subramanian (1988).*

south Indian region. Most of central India is underlain by Deccan traps, whereas the southern region is underlain by the shield area hard rocks, thus suggesting that local geology exerts a major control over the sediment yields of the tropical river of India. There are no well defined drainage systems in the areas shown by the unshaded portions of the map and hence the erosion rates in these regions are expected to be close to zero.

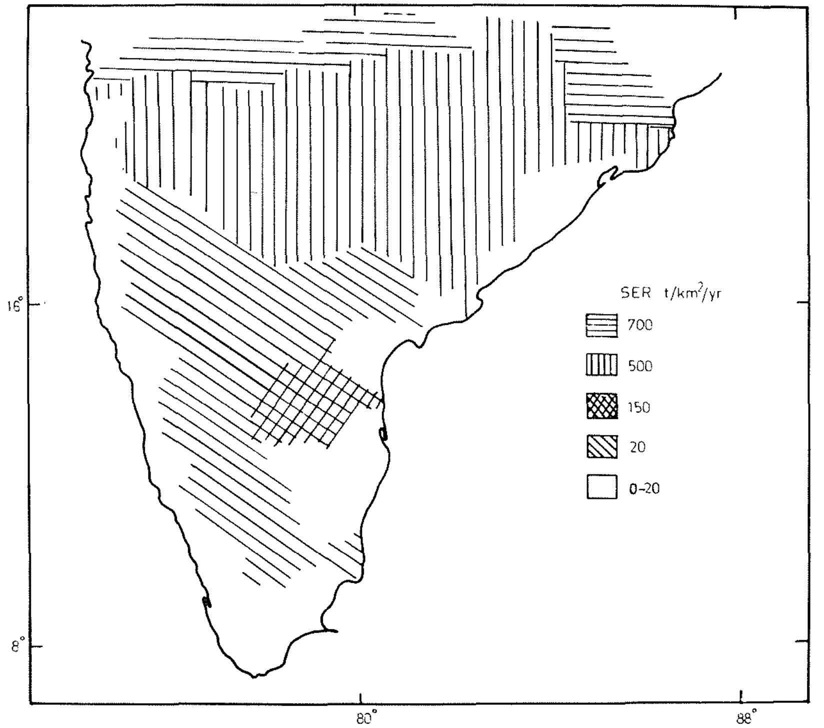

Fig. 3 Sediment yields (SER) in the tropical Indian region.

Discharge

The relationship between river flow and sediment transport has been studied by many workers (e.g. Leopold *et al.*., 1964; Probst, 1986). Figure 4 shows the relationship between discharge and sediment transport for the Cauvery River at its mouth. Similar relationships were obtained at all other stations on the river and also for the Godavari River (Biksham & Subramanian, 1988).

Human influence

While basin geology and discharge exert a major control over sediment yield in these tropical river basins, the delivery of sediment by these rivers, particularly the Krishna and Cauvery, has been influenced by the construction

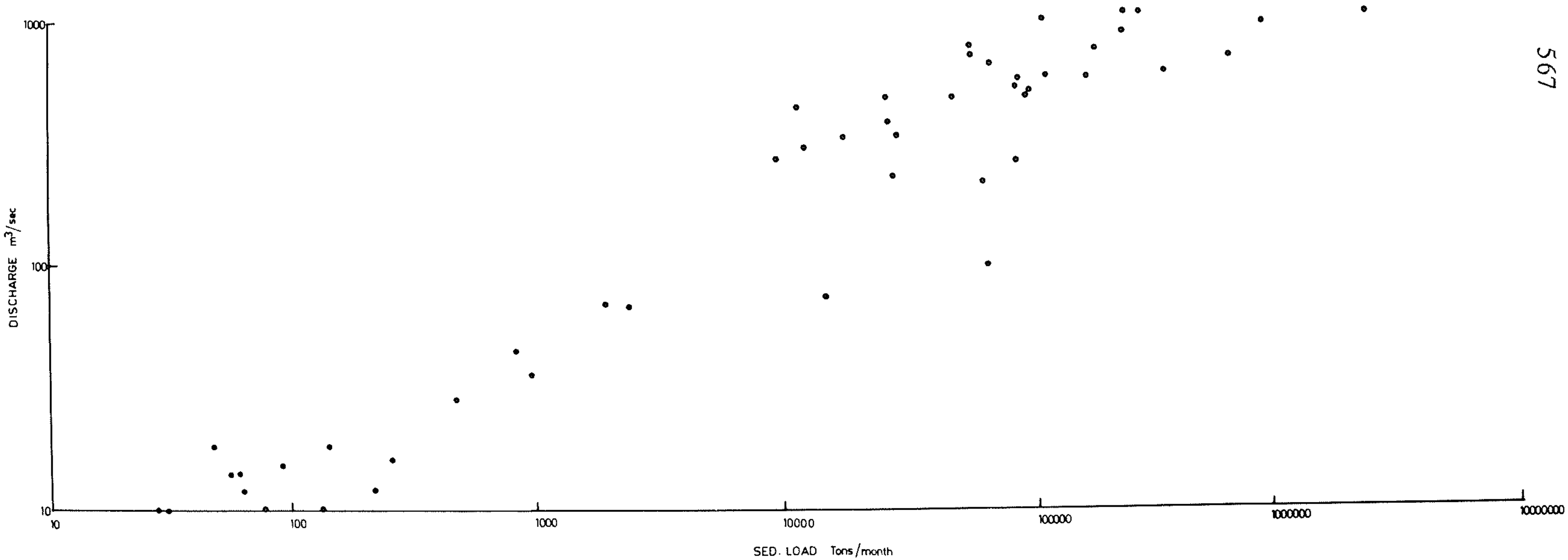

Fig. 4 *The relationship between discharge and sediment load for the Cauvery River.*

of dams and diversion channels (locally known as anicut) which act as efficient sediment traps. This is particularly evident in the Krishna River, where the measuring station at Vijayawada lies below two major dams. Figure 5 indicates that values of suspended sediment concentration in the river decrease sharply downstream of the dam region (beyond Srisailam). The values indicated by the dashed line suggest a substantial loss between Srisailam and Vijayawada (Subramanian, 1982). A downstream decrease in sediment concentration has been reported for a number of world rivers (Gibbs, 1967; Meybeck, 1976).

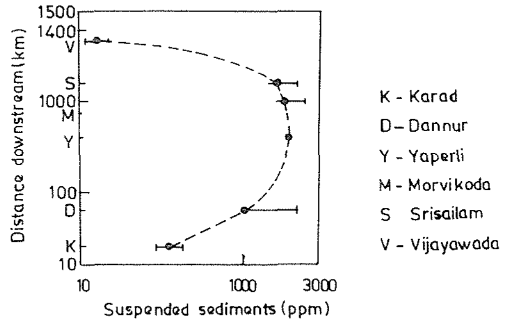

Fig. 5 Downstream variation of suspended sediment concentrations in the Krishna River.

TEMPORAL VARIATIONS IN SEDIMENT TRANSPORT

Annual

The interannual variation of sediment transport by the Godavari, Krishna and Cauvery is shown in Fig. 6. The fluctuations in the annual sediment load of these rivers can be attributed to variations in the annual runoff and the degree of human interferences (agricultural activity, effects of reservoirs etc.). For example, the water discharge at Musiri on the Cauvery River during the year 1976–1977 was extremely low (126 m^3 s^{-1}) and accounts for the decrease in the sediment load of the river during that period.

Seasonal

The monsoon rainfall exerts an important control over the water and sediment discharge by the tropical Indian rivers. Over 95% of the sediment load of the Godavari and Krishna and over 90% of the sediment load of the Cauvery are transported during the monsoon period (Table 1). The maximum recorded discharge and sediment load during the non-monsoon season at the mouth of the Godavari are 0.04% and 6.7% respectively of their annual load (Biksham & Subramanian, 1988).

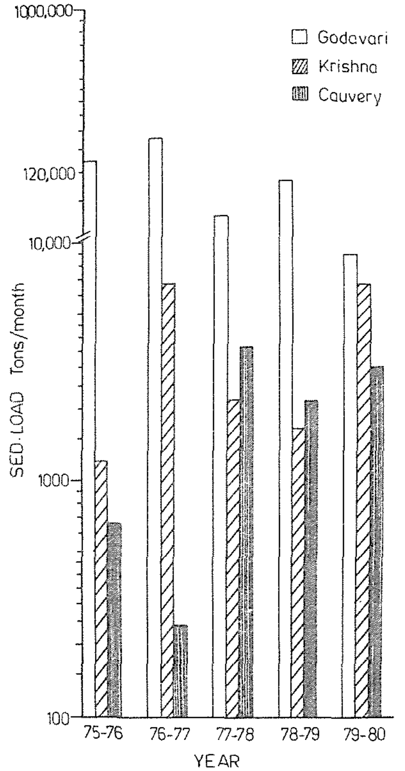

Fig. 6 Variation in annual suspended sediment loads.

Monthly

The monthly variation in material transport by tropical rivers is linked to fluctuations in river discharge. Figure 7 shows the monthly variations in river discharge and sediment load of the Cauvery River. Both runoff and sediment load reach their maximum during the monsoon months of July to December. They peak in November in the Cauvery and in August in the Krishna and Godavari.

Daily

Daily sediment transport data for two years from the Godavari River (1977–1978 and 1978–1979) indicate that on certain days the sediment transport can account for 5–18% of the annual load. According to Biksham & Subramanian (1988) the Godavari transported more than 7 million tonnes of sediment on 5 August 1979 and 15 July 1978, which is three times higher than the mean daily load of the world's largest river, the Amazon (Meade *et al.*, 1979). Thus in the case of tropical Indian rivers, particularly the Godavari, a few days in the year may be responsible for transporting most of the annual sediment yield from the river basin.

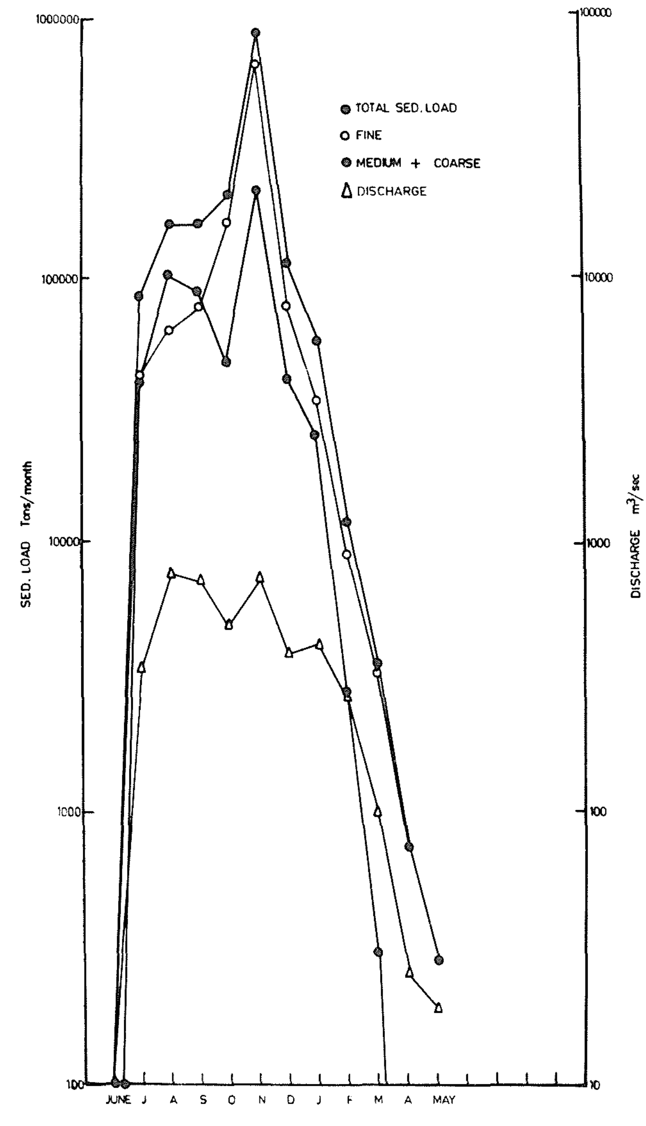

Fig. 7 *Monthly variation of discharge and the magnitude and grain size composition of the sediment load in the Cauvery River.*

GRAIN SIZE AND SEDIMENT LOAD

Table 3 summarizes the size distribution of the suspended sediment. Fine sediment dominates the sediment load of tropical Indian rivers. Since the granite and other hard rocks in the Cauvery basin consist primarily of quartz and feldspar they release more coarse sediment to the river and as a result the coarse fraction is higher in this river. At the Krishna River mouth, fine particles are more dominant because the coarser particles are trapped by the

Table 3 *The contribution of individual size fractions to the total sediment load*

River	*Course size fraction (>200 μm)*		*Medium size fraction (200-75 μm)*		*Fine size fraction (<75 μm)*	
	Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*
Godavari	*2-60*	*23*	*3-70*	*33*	*39-191*	*114*
	(2-23)	*(14)*	*(5-30)*	*(19)*	*(49-87)*	*(67)*
Krishna	*0.005-2.2*	*0.80*	*2-3.7*	*1.7*	*1.9-10.4*	*5.2*
	(2-14)	*(10)*	*(9-23)*	*(22)*	*(63-89)*	*(68)*
Cauvery	*0.002-0.7*	*0.4*	*0.0001-0.5*	*0.2*	*0.2-2.7*	*1.1*
	(9-37)	*(21)*	*(4-20)*	*(12)*	*(43-87)*	*(67)*

Figures in parentheses indicate percentages.

dams between Srisailam and Vijayawada and only the finer particles reach the river mouth.

Figure 7 shows that in the Cauvery River, during low discharge periods of April, May and June, the transport of the coarse and medium size fractions becomes negligible and the total sediment load is composed almost entirely of finer particles. During the subsequent increase in discharge, the loads associated with all size fractions (fine, medium + coarse) increase, following a more or less similar trend. The grain size of the sediment load directly affects sediment chemistry and hence the elemental cycle within the hydrosphere.

Variations in the sediment load of a river at any location may reflect differential contributions from specific size fractions (Subramanian, 1987). Taking the Krishna (at Vijayawada) as an example, it can be seen from Fig. 8 that the fine fraction represents a major proportion of the monthly sediment load of the river. Different sediment loads may be characterized by specific mineral populations due to selective sorting in the transport process.

Mineralogical changes in river sediments generally reflect particle size control. Detritals such as quartz and feldspar are normally distributed over a wide spectrum of sizes, whereas sheet silicates are dominant in the finer size ranges. Table 4 lists the mineralogical characteristics of suspended sediment from the mouths of the Godavari, Krishna and Cauvery Rivers. They transport predominantly montmorillonite-type clays, whereas the Himalayan rivers carry predominantly illite-kaolinite groups. Hence, the tropical rivers have sediments which can be more chemically active. Though the combined sediment load of these tropical rivers is negligible compared to the Himalayan drainage system, their mineralogical signature, in terms of fine-particle mineralogy, can be seen even in the Ganges cone in the Bay of Bengal (Mallick, 1976; Subramanian, 1980).

DEPOSITION

Deposition rates calculated for tropical Indian rivers by the excess ^{210}Pb

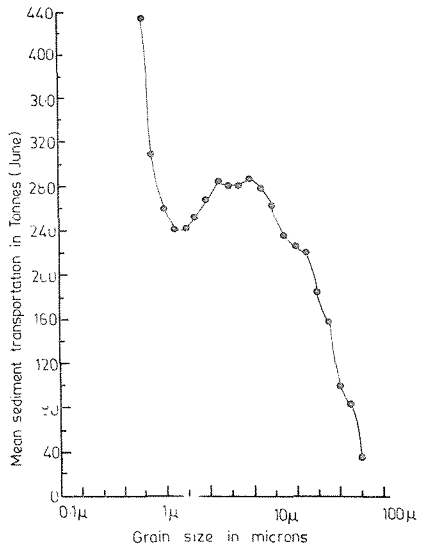

Fig. 8 *Particle size distribution of the monthly (June, 1984) sediment load of the Krishna River at Vijayawada.*

Table 4 *Mineral composition of suspended sediments (%)*

	Godavari	*Krishna*	*Cauvery*
Feldspar	2.6	9.7	36.4
Quartz	5.2	6.5	4.9
Amphibole	-	1.6	3.0
Kaolinite	2.6	3.2	23.0
Illite	2.6	1.6	4.9
MCL	4.0	1.0	5.0
Montmorillonite	85.8	76.4	23.0

technique were plotted against sediment erosion rate (SER). Figure 9 indicates the relationship between the two rates. Both rates relate to the river mouth region. In the case of the Tunghabadra and Amaravathi Rivers which are tributaries of the Krishna and the Cauvery respectively, the rates are for a station just before they joint the main river. The negative relationship indicates that when a large quantity of sediment is transported due to high erosion rates, as in the case of the Godavari, not all the sediment is deposited in the river basin. On the other hand, for rivers carrying low sediment loads, such as the Krishna and the Cauvery, the bulk of the sediment is deposited at the river mouth itself. Subsequently delivery of sediment to the Bay of Bengal indicates that localised erosion in the deltaic regions of these rivers causes a small supply of sediment to the adjacent marine environment. It must however be recognised that the estimates of deposition derived from excess ^{210}Pb measurements might be overestimates due to internal disturbance after the sediments re-buried. As such the rate of deposition indicated in Fig. 9 might therefore represent an upper

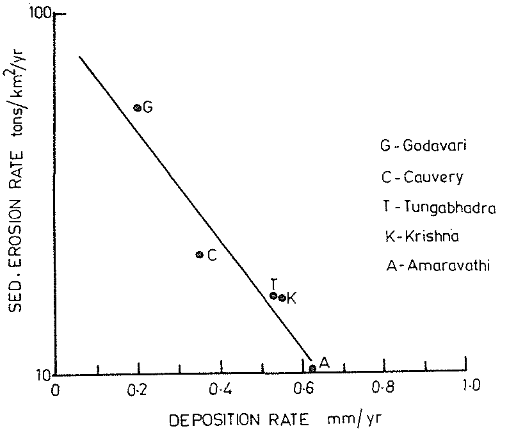

Fig. 9 Sediment yield deposition rate relationships for tropical Indian rivers.

limit. The true rates of deposition in the deltaic region are perhaps lower than these values. In addition to internal disturbances after the sediments are buried, the construction of a number of dams and diversion channels has artificially enhanced the rate of deposition. Hence it is very difficult to accurately calculate the mass balance of sediments eroded and deposited in the river basin.

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